On the Diurnal Variations of the Electric Waves Occurring in Nature, and on the Propagation of Electric Waves Round the Bend of the Earth.

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Since the earliest days of electric wave telegraphy it has been known that there exist natural electric waves which frequently affect the receiving apparatus at a wireless telegraph station more powerfully than do the message-bearing waves. In the telephonic method of receiving signals, where the apparatus is so arranged that the effect of a train of waves is to cause a pulse of electric current to pass from the "detector" through the telephones, the natural electric waves make themselves evident as clicks, or as rattling noises, in the telephones. They are easily distinguished from signals, for the sounds produced by the latter are more regular, and, in fact, are often musical in character. The natural electric waves are doubtless due to electric discharges taking place between masses of electrified air, or between such masses and the earth. Till recently it was not known whether the discharges affecting any particular station were taking place at distances of hundreds of miles or at distances of thousands of miles from the station; but it is now certain that for stations in England the distances concerned must usually be reckoned in thousands of miles. This point was settled by tracing and identifying individual natural wave trains at two receiving stations, one in London and the other in Newcastle.* It was found that about 70 per cent. of the natural wave trains perceived at one station could be identified with those perceived at the other, and, further, that more than half of these were of much the same intensity at both stations—from which it may fairly be inferred that the distance of the discharge is great compared with the distance between the stations.†

The number of natural wave trains, or "strays" as they are commonly called for brevity, received at any station varies in general from hour to hour. In England these variations are most pronounced during the summer months, principally on account of the frequency of local lightning storms during these months. (The word local is here intended to mean within a

* Eccles and Airy, 'Roy. Soc. Proc.,' 1911, A, vol. 85.

† In all that follows it is assumed that the sources of the wave trains are not extra-terrestrial.

radius of two or three hundred miles of the receiving station.) During the winter months, on the contrary, the number and intensity of the strays are relatively regular. The study of the phenomena belonging to the strays of distant origin may clearly be more favourably pursued in the winter than in summer, since the confusing feature of local lightning discharge is absent in winter. Besides the seasonal variations in the number and the intensity of the strays there is at every station a well-marked diurnal variation. Leaving out the irregularities due to local storms, we may say that the strays are in general more frequent and numerous during the night hours than during the day hours. The variations may be represented graphically as a curve in any of the methods indicated below and then they appear as shown in fig. 1, which may be regarded as a typical 24 hours' continuous record of the integral of number and intensity. These diurnal

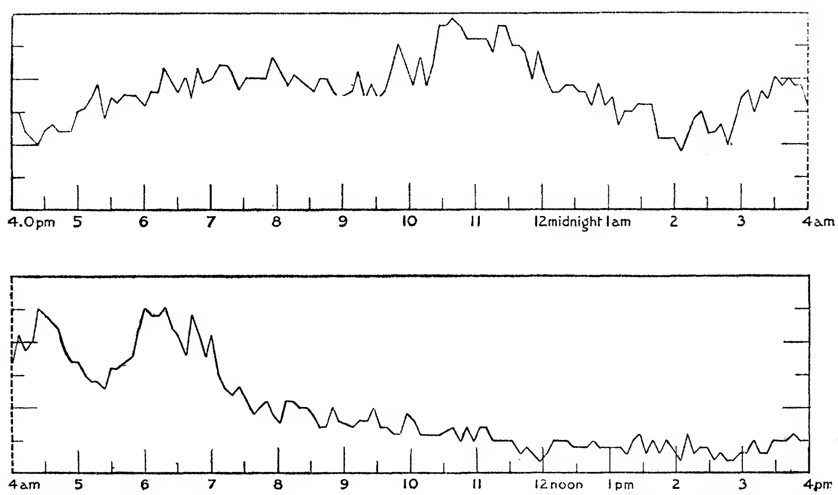

FIG. 1.—Twenty-four hours' Continuous Record of Integral Intensity of Strays, November 14 and 15, 1910.

variations have not yet been investigated thoroughly. The author has not been able to find any account of observations in which the effects of local storms have been eliminated.

From what has been said it is plain that the most interesting parts of the diurnal curve are those at which day and night conditions meet and change one into the other. To investigate these important parts of the curve the ordinary apparatus of a wireless telegraph station may be utilised. The apparatus employed by the author consisted of an antenna of 12 wires sloping from south to north at an angle of about 45° from a height of 170 feet, connected at the bottom to a coil of variable inductance, which was in turn

connected to an earth plate. The inductance was usually about 6×10^6 cm., and the natural period of the antenna was about 50,000 per second—which corresponds to a wave-length of about 6000 metres. This frequency was selected merely because it was of the same order of magnitude as that of the Marconi Transatlantic stations, signals from which were also being measured from time to time. The antenna inductance engaged inductively with another coil forming part of a secondary circuit that could be tuned to the antenna by aid of a variable condenser in it. A detector and telephone were connected with the circuit in the ordinary way. The Pickard zincite-chalcopyrite detector was used.

With such apparatus several ways of making and recording observations present themselves. The easiest and most obvious method consists in listening at sunrise and sunset to the noises made in the telephone by the natural electric wave trains; other methods involve the use of a galvanometer in place of a telephone receiver. The observations in this paper were practically all made with the telephone. A careful listener will find that on a typical morning the following phenomena appear:—First, starting to listen about half an hour before sunrise, the strays heard in the telephone are loud and numerous and much as they have been all night; then about 15 minutes before sunrise a change sets in, the strays get weaker and fewer rather quickly, till at about 10 minutes before sunrise a distinct lull occurs, of perhaps a minute's duration. At this period there is sometimes complete silence. Then the strays begin to appear again, and within 10 minutes of the lull they have settled down to the steady stream proper to the daytime. These day strays are weaker and fewer than the night strays, except on rare occasions. The lull is sometimes very pronounced, and at other times there is no lull at all. It is usually more marked at sunset than at sunrise.

The simplest way of representing these events, just as they are heard in the telephone, is by a hand-written record of the sounds. With practice, it becomes easy to make pencil marks on paper ruled in convenient units of time in such a way that the height of the mark represents the intensity of the sound, and the general shape of the mark the duration and character of the sound. Some of the records that have been obtained in this way are reproduced in figs. 2 to 5. These are selected out of a large number of records as examples of the different kinds of minima obtained at both sunrise and sunset. It will be noticed that at sunset the minimum is about 10 minutes after the calendar time of setting. Records such as these can be made to yield quantitative results of sufficient accuracy for the discussion of so irregular a phenomenon, by plotting rough estimates of the time integral of the intensity of the strays, that is, by estimating the

aggregate area of the representative marks in any convenient intervals of time. The value of this time integral taken over, say, two minutes, is treated as the ordinate corresponding to the middle moment of the interval, which is taken as abscissa and a smooth curve drawn. But an even rougher method, consisting of counting the number of marks in each two minutes' interval, and using these numbers as ordinates corresponding

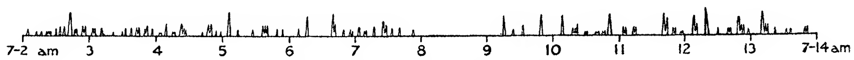

Fig. 2.—Strays, November 14, 1909. Sun rises at 7.17 A.M.

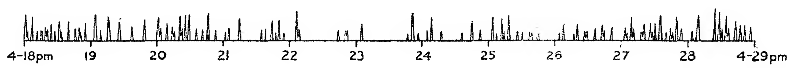

Fig. 3.—Strays, November 13, 1911. Sun sets at 4.13 P.M.

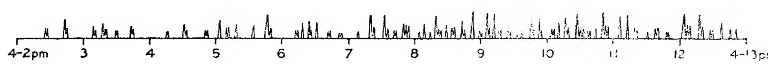

Fig. 4.—Strays, November 23, 1911. Sun sets at 4.0 P.M.

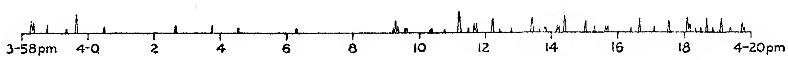

Fig. 5.—Strays. December 9, 1911. Sun sets at 3.50 P.M.

to the mid-times, may suffice in many cases. Of course, a theoretically more perfect procedure would be to pass the detector currents through a sensitive galvanometer possessing a heavy moving system. A time record of the deflections indicated by the instrument would, at first sight, give a better quantitative result than the hand-made record just described; but actual trials show that there is an increase of accuracy only when the strays are very numerous, more numerous, in fact, than on the average occasion. Adopting, then, the method already described, we obtain curves such as that of fig. 6. These observations were made at the author's laboratory in London.

The scientific value or importance of an isolated result like the present one

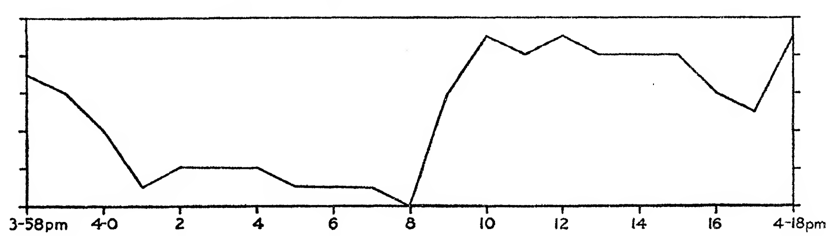

Fig. 6.—Integral Intensity Curve, Sunset, December 9, 1911.

may be regarded as very small in itself. But, in the present case, the result is so completely inexplicable by the ordinary conceptions of the propagation of electric waves through the atmosphere, that we are compelled by its refusal to fit into the accepted scheme of things to attempt an extension of that scheme. Now, in searching for an explanation of these twilight minima, we have to notice that there are two main alternative possibilities. In the first place, the atmospheric discharges that produce the strays may themselves, for some reason, become temporarily infrequent at twilight; and, in the second place, the space through which the waves travel may become temporarily less easily traversed in twilight. The former alternative, when taken in conjunction with the author's experience over nearly 20° of longitude that it is the receiving station's local time which is concerned, implies that the bulk of the strays received at a given station are produced by atmospheric discharges occurring in regions of the atmosphere that have the same sunset and sunrise as that station; or, in other words, implies that the strays observed have their origin at places on (roughly) the meridian of the receiving station. Evidence has been already quoted, however, to show that the larger proportion of the strays observed at any station usually originate at a great distance from the station; hence the alternative under discussion leads to the unlikely conclusion that every station receives its strays from atmospheric discharges occurring at a great distance along its own meridian, and from that place solely.

We turn, therefore, to the other alternative, that the propagation of electric waves towards any place is hindered by some unknown effect of twilight. That this latter alternative is really the correct one is strongly indicated by observations (to be described later) on artificial electric waves coming from considerable distances.

Electric waves travelling near the earth's surface might conceivably be affected by the presence or absence of the sun at a point of observation in two obvious ways: First, light may ionise the air locally in sufficient degree to cause considerable absorption of the energy of the waves; and, secondly, sunlight might affect the electrical resistance of the ground within, say, 50 miles round the antenna, and thus have an effect on the absorption of the waves when they run over this region. Considering the former hypothesis first, the atmospheric absorption by ionisation due to solar radiation must, if it exists, be greater in strong sunshine than during twilight, which is contrary to observation. In point of fact, the absorption arrived at in this manner is, as will be shown incidentally later, much too small at any time of day to produce the effects actually observed. Moreover, it has long been known that the propagation of electric waves over short distances is

practically as perfect in strong sunlight as in the dark. On all these counts, therefore, the supposition that the minima phenomena under discussion can be explained by ionisation of the lower layers of the atmosphere must be discarded as untenable.

We must therefore turn to the possibility of alterations in the resistance of the ground round the antenna, alterations of such a nature that the waves are absorbed much more freely during a certain few minutes of twilight than before or after. Here we may at the same time consider a subordinate possibility, namely, that the resistance of the ground within a few yards of the earth plates of the antenna might vary through a minimum value during twilight. If this really happened there would be extra dissipation near the earth plate of the energy of the oscillations excited on the antenna by the incoming waves. Both of these views have been negatived by the author's observations on signals coming from short distances, which show that signals originating at distances of less than 50 miles do not undergo appreciable diminution in strength, even on days when the stray minimum is well marked. But, to make certain of the non-existence of the subordinate possibility just referred to, a long series of determinations was made, during the past autumn, of the high-frequency resistance of the antenna and its earth connection at various frequencies and at various times of the day; and especially at the twilight periods. These measurements were carried out by two distinct and trustworthy methods. The details of the determinations need not be given here; it is sufficient to state that the results leave no doubt that the local earth resistance does not vary in the rapid manner, nor to the wide extent, that is required to explain the twilight minima of the strays.

Another point that supports the view that the stray minimum is not produced by strictly local causes may be stated here. It is very noticeable that the twilight minima are easier to observe when the receiving apparatus is adjusted for long waves (say 6000 metres) than when it is adjusted for short waves (say 1000 metres). This is of obvious significance when taken with the fact that signal waves of great length are most suitable for communication over great distances. Now the most striking difference between signals received from long and from short distances is that in the former case the curvature of the earth may exert appreciable, perhaps very great, influence on the signal intensity.

This immediately raises the question of the manner of propagation of long electric waves round the earth. The fact is now thoroughly established that signal-bearing waves can travel a quarter of the way round the globe and still be easily perceptible. That this is not a manifestation of ordinary

diffraction has been thoroughly settled by the investigations of Rayleigh, Poincaré, Macdonald, Nicholson, and others, whose work has shown irrefutably that the energy propagated round a quarter of the globe by the process of diffraction would be utterly inappreciable. Heaviside has suggested that, in the type of waves used in wireless telegraphy, the Faraday lines of electric force are attached, as it were, to the earth, and slide along its surface, and that therefore they cannot leave it; but this view, in fact, throws us back on the diffraction result. Again, in 1906, Zenneck added to this suggestion a consideration based on a well-known illustration of Poynting's theorem. In his original memoir* on the propagation of energy in the electromagnetic field, Poynting gives as an illustration of the theorem the case of a wire possessing resistance and carrying an electric current. Heaviside,† referring to this illustration, showed that the moving electric field cannot be purely radial; in other words, the Faraday lines belonging to the flowing electricity must lean forward as they move along the wire—so that the energy vector shall have a component perpendicular to the surface of the wire. This particular case has been worked out in great detail since the date of the memoir, but Zenneck's application was to the simple case of the propagation of a plane wave over a badly conducting solid, such as the earth, with a plane boundary. His suggestion is, briefly, that the tilting forward of the wave fronts near the conductor will lead to a general slow turning downward of the waves towards the earth, so that a large proportion of the energy of the waves will be deflected round the bend of the earth instead of being propagated linearly into space. This suggestion does not in reality assist the pure diffraction theory at all.

Another hypothesis was put forward by Heaviside in 1900, when he suggested that the attenuated gases of the upper atmosphere might provide a conducting surface concentric with the earth, between which and the surface of the earth itself the waves might spread with two-dimensional divergence. This hypothesis has not yet been supported or denied by any trustworthy experiments or observations. Such experiments or observations will necessarily have to be made on waves that have travelled long distances, for the upper layers of the atmosphere cannot be greatly concerned in short-distance transmission. But it will be perceived, from the remarks already made on the minima of natural electric waves, that this upper conducting layer might supply the explanation of the phenomenon, and thereby gain some support. On examination, however, it appears that the phenomenon cannot be explained by means of the bare hypothesis, and still less can the

* 'Phil. Trans.,' Jan. 10, 1884.

† 'Electrical Papers,' vol. 2, p. 94.

other recorded facts of long-distance transmission be explained. The writer has therefore investigated another, and closely related, possibility, which, it turns out, throws light on the causes of the stray minimum, as well as on many of the observed facts of long-distance transmission. To these new considerations we now turn.

The hypothesis to be introduced is based on the influence of the ionisation of the air on the propagation of electric waves through it. It is well known that, under normal conditions, the air at the sea-level is only slightly ionised even in strong sunshine, and that at a height of a few miles above the earth's surface the ionisation is, according to observations from balloons, sometimes 20 times as great as at the surface. Higher still the ionisation doubtless increases further, on account of the more and more intense ionising action of the solar radiation, which, it is plain, must be greater in these higher and rarer regions than in the dense regions below. No law can be legitimately assigned for the computation of this gradual transition from low conductivity to high conductivity, yet, for the purpose in hand, it is necessary to form some idea of the effect of this heterogeneity on the propagation of electric waves.

It is first necessary to examine the effect of charged ions of molecular mass on the velocity of the waves, and here we may follow, with suitable modifications, the standard methods applied to the study of optical dispersion in media containing electrons. Let e be the charge, m the mass, of each ion, and let n be the number of ions per cubic centimetre at a point whose co-ordinates are x, y, z, referred to a right-handed rectangular frame of axes with the axis of z vertical. Suppose that electric waves are advancing through the medium in the positive direction of the x axis, and with electric force Z, magnetic force β, at the point x, y, z. Then if μ be the permeability of the medium and κ the dielectric constant of the unionised air,

$$\frac{\partial Z}{\partial x} = \mu \frac{d\beta}{dt} \quad \text{and} \quad \frac{\partial \beta}{\partial x} = \kappa \frac{dZ}{dt} + 4\pi n e \frac{d\zeta}{dt},$$

where ζ indicates the displacement of each ion from its original position produced by the waves. The equation of motion of an ion is

$$m\frac{d^2\zeta}{dt^2} + f\frac{d\zeta}{dt} = eZ,$$

where f is a frictional constant of viscous type.

If the time factor in Z be ϵ^{ipt}, this equation becomes

$$\frac{d\zeta}{dt} = \frac{eZ}{mip+f}.$$

Eliminating β and ζ among these three equations, we have

$$\frac{\partial^2 Z}{\partial x^2} = \mu\kappa \frac{\partial^2 Z}{dt^2} + \frac{4\pi\mu n e^2}{mip+f}\frac{\partial Z}{\partial t}.$$

There is a solution of the form

$$Z = \epsilon^{-lx+ip(t-x/v)}$$

for waves of frequency $p/2\pi$, if the velocity

$$v = \frac{mp}{\gamma f}\sqrt{\left(\frac{2(1-\gamma)}{\mu\kappa}\right)}\left\{\sqrt{\left[1+\left(\frac{\gamma f}{mp(1-\gamma)}\right)^2\right]}-1\right\}^{\frac{1}{2}}$$

and the absorption factor $\qquad l = \frac{\mu\kappa\gamma f}{2m}v.$

Here γ has been put for the quantity

$$\frac{4\pi n e^2 m}{\kappa(m^2p^2+f^2)},$$

which, it will be shown, is usually smaller than unity. In addition, the quantity $\gamma f/mp(1-\gamma)$ is usually very small compared with unity, hence, approximately,

$$v = \frac{1}{\sqrt{(\mu\kappa)}}(1+\tfrac{1}{2}\gamma), \qquad l = \frac{\sqrt{(\mu\kappa)}f}{2m}\gamma(1+\tfrac{1}{2}\gamma);$$

or the absorption coefficient per wave-length is

$$l' = \frac{\pi}{1-\gamma}\frac{\gamma f}{mp}.$$

It should be mentioned that, in forming the equations, it has been implicitly assumed that the ions are so heavy that they acquire only small velocities and make very small excursions under the action of the waves. That is to say, the ions are supposed to be collections of molecules, or, at the smallest, single molecules. The absorption in the case of very small ions, that is, electrons, has been worked out by J. J. Thomson,* and involves different considerations from those appropriate here.

Rough estimates of the various magnitudes involved in the last equations may be obtained by using the results of laboratory experiments on ionised gases, though, unfortunately, there are as yet but very few data available on the ionisation of air by solar radiation. First notice that the friction coefficient f can be estimated from experiments on the terminal velocities of ions in various gases. From the equation of motion of an ion we see that its terminal velocity under a steadily applied electric field Z is

$$\frac{d\zeta}{dt} = \frac{e}{f}Z.$$

* 'Phil. Mag.,' August, 1902, p. 253.

In air under standard conditions $d\zeta/dt = 1{\cdot}5$ cm./sec. in a field having a gradient of 1 volt per centimetre. Take $e = 1{\cdot}0 \times 10^{-20}$ in electromagnetic units, then $f = 7 \times 10^{-13}$, roughly. Again taking $p = 10^7$ and $m = 2 \times 10^{-21}$ in grammes, then $mp = 2 \times 10^{-14}$. Thus for waves of the order of frequency 1,000,000 per second, the two terms in the denominator of the quantity γ are of about the same order of importance at low levels in the atmosphere. For waves of lower frequency the term f^2 is much more important than the term m^2p^2, which may then be neglected in the denominator of γ. At higher levels, on the contrary, the term f^2 probably becomes negligible in comparison with m^2p^2 since the value of f is known to fall off much faster than that of m as the rarefaction increases. Thus, at high levels, we have

$$\gamma = 4\pi ne^2/\kappa mp^2, \text{ approximately.}$$

At low levels the value of γ works out as $0{\cdot}55 \times 10^{-14} \times n$ with the numbers already assumed. The number of ions per cubic centimetre at sea level is often given as between 1000 and 10,000. Thus γ is quite negligible compared with unity if this estimate of n and that of f are valid. At high levels, using the last equation, we find $\gamma = 0{\cdot}6 \times 10^{-11} \times n$ for $p = 10^7$ (corresponding to a wave-length of nearly 200 metres) and $\gamma = 0{\cdot}6 \times 10^{-9} \times n$ for $p = 10^6$ (corresponding to a wave-length of nearly 2000 metres in ordinary air). It is more than probable, however, that at moderately high levels, where the air is rather rarefied—for example, at a height of 20 miles the pressure is, on the theory of convective equilibrium, about 1/100 of the pressure at sea level—the ion is of much smaller mass, say 100 times smaller, than is assumed above, and this would make the last figure become $\gamma = 0{\cdot}6 \times 10^{-7} \times n$ for $p = 10^6$.

For convenience in discussion, the portion of the atmosphere below the permanently conducting layer and throughout which the equation

$$\gamma = 4\pi ne^2/\kappa mp^2$$

holds good, that is the portion of the atmosphere which is ionised strongly and directly by the sun, will be called the middle atmosphere. The part below this will be called the lower atmosphere, and here the equation

$$\gamma = 4\pi ne^2 m/\kappa f^2$$

is probably appropriate while n has low values. Of the middle atmosphere and of the upper atmosphere we know nothing directly. Perhaps the best information available is that contained in the memoirs of P. Lenard and C. Ramsauer,* who showed that the ultra-violet light of the sun will produce in air two effects of interest in the present connection. One effect is that the ultra-violet light, and possibly the cathode rays, of the sun produce electrical carriers of

* 'Heidelberger Akademie Sitzungsber.,' 1910—11.

molecular size, and the other is that these same agencies also produce, by direct action on the gases of the atmosphere, condensation nuclei consisting of solid or liquid compounds which are not electrically charged when first formed. Evidently, the condensation nuclei can have only slight influence on the value of the quantity γ as compared with the electrical carriers of molecular size. These heavy ions, or condensation nuclei, doubtless frequently become charged by attaching one or more of the light ions, which has the effect of putting such ions out of action for our purposes. The lighter ions are probably in a majority in the higher parts of the middle atmosphere, and the heavy ions in a majority in the lower parts, and also in the lower atmosphere. It may be mentioned that the heavier ions found in the lower atmosphere, whether consequences of solar radiation or not, escape being counted by the kind of apparatus usually used in measurements of atmospheric electricity, on account of their immobility.

So far as the quantity γ is concerned the principal difference between day and night conditions, and between the conditions at different times of the day, is due to the variations of the number of ions per cubic centimetre provided by solar radiation. It is not possible to be precise on this matter, even in the lower atmosphere. But, broadly, it is clear that the value of n in the lower and middle atmospheres must vary considerably with the obliquity of the sun's rays at the place, that is to say, with the season and the time of day, and also must vary profoundly from daylight to darkness. About the time of sunrise at any particular place the process of ionisation by the solar radiation will be occurring at all heights of the atmosphere over an area extending many miles to east and west of the place; at sunset recombination of the ions will occur through a similar space. Of course the layers nearest the earth will be least disturbed in electrical constitution, mainly for the reason that the sun's rays must have been robbed of much of their ionising powers by the time they reach low levels; but it is known from direct observations at various levels up to heights of several miles that the influence of the sun is quite perceptible. But, in fact, it is easily seen from the formula deduced above for the absorption per wave-length, that the normal ionisation observed in the lower atmosphere produces inappreciable absorption of the waves at any time of day over terrestrial distances.

Our knowledge of the conditions ruling in the hours of darkness is even less precise than that of the day conditions. The very rapid rate of recombination of ions when the ionising agent is removed points to the possibility of the middle atmosphere being perfectly free from ions during darkness. But it is probable that there occurs during the day a great sifting of oppositely charged ions under the operation of the earth's vertical electric field, positive

ions moving up and negative ions moving down, with the result that some parts of the middle atmosphere may remain ionised after the sun has set. If we suppose, however, that the ions do for the most part recombine, then the effect of the change from day to night is to remove a veil, as it were, of ionised air from between the upper conducting layer and the earth.

Since the velocity of the waves in the sunlit middle atmosphere is greater the higher the level at which they are travelling, a ray of electric radiation starting from a point of the earth's surface in a direction inclined slightly upward will pursue a straight path in the lower atmosphere and a slightly bent path, with its concavity downwards, in the middle atmosphere, thus following to a greater or less extent the curvature of the earth. If its curvature in the middle atmosphere is on the average greater than that of the earth—and not otherwise—the ray will be turned down to the lower atmosphere and will again traverse a straight line. In other words, the wave-fronts will be tilted forward as they travel, in a manner quite analogous to the refraction of sound in air when the temperature varies upward. This bending of the rays may be given for shortness the name ionic refraction; it would be very rapid in layers where γ approached unity. Thus the radiations diverging in all directions from a lightning stroke or from a wireless telegraph antenna become confined in the day between the conducting surface of the earth and a certain level in the middle atmosphere. Even the rays that start horizontally from a place on the earth's surface must, owing to the earth's curvature, reach, within 300 miles of the source, to heights where the air may be expected to be strongly ionised, and must then suffer refraction downwards. Since the quantity γ is inversely proportional to the frequency of the transmitted waves, the limiting height of penetration of the waves is smaller the lower the frequency, and therefore low-frequency waves become concentrated nearer to the earth's surface than do higher frequency waves.

The curvature of the trajectory of waves travelling at a height z is $dv/(vdz)$, v being the velocity at the place. But when γ is small $v = (1+\frac{1}{2}\gamma)/\sqrt{(\mu\kappa)}$, and therefore the curvature is $\frac{1}{2}d\gamma/dz$ approximately. If we assume a condition of things in which the radius of curvature of rays at all heights is $r+z$, where r is the radius of the earth, and that $\gamma = 0$ at $z = 0$, we find

$$\gamma = 2\log\frac{r+z}{r} = 2\frac{z}{r}, \text{ approximately.}$$

Though, in fact, the bending of rays in the lower atmosphere is probably not so great as this, the equation indicates that the order of magnitude of γ required in the middle atmosphere at, say, a height of 20 miles is about

0·01. This in turn indicates that the number of ions per cubic centimetre should be about 160,000 when the wave-length is 2000 metres, and about 16,000 when the wave-length is 6000 metres. Such ionic concentrations are not improbable.

It may be objected that there has as yet been no experimental corroboration of this concentration of the energy of the waves into a comparatively thin stratum near the surface of the earth. But as a fact no measurements have as yet been carried out over great distances on the variation of intensity of signals with distance and under unvarying atmospheric conditions; and clearly the measurements that have been made over short distances—which all support the inverse square law as was to be expected—cannot have any bearing on refractions that take place in high layers. When measurements of intensity over distances of 1000 to 2000 miles become available it may be expected that the inverse square law will hold for a distance of three or four hundred miles, and after that a law indicating rather less divergence may hold for several hundred miles more, if the frequency is low enough for the ionic refraction to produce bending at least as great as the convexity of the globe.*

We now proceed to the explanation of the stray minima described earlier. In the first place it is evident that if the surfaces of equal ionisation in a

* Since the above was written, an account by L. W. Austin ('Washington Bureau of Standards Bulletin,' October, 1911) of some new measurements of the intensity of signals has come to hand, which appears to strengthen the author's position greatly, so far as the measurements go. The inverse square law for the divergence of energy shows that $I \propto x^{-1}$, where I is the intensity of the current received on an antenna, and x is the distance of the sending station. If the waves were travelling in free space of electrical constitution like that of our lower atmosphere, the absorption would demand a formula of the type

$$I \propto x^{-1}\epsilon^{-ax},$$

where a is independent of the wave-length. Also it has been shown above that if the waves were travelling in free space filled with air highly ionised, the absorption would require a formula of the type

$$I \propto x^{-1}\epsilon^{-ax\lambda^2},$$

where a is again independent of the wave-length. Now, the observations quoted support an empirical formula very different from either of these, namely,

$$I \propto x^{-1}\epsilon^{-ax/\sqrt{\lambda}}.$$

A formula involving the wave-length in this manner is not suggested, and cannot even be accounted for, by absorption in an ionised atmosphere or in a badly conducting surface such as that of land or sea; but it is clearly in rough general accord with the law, developed in this paper, that the desired bending of the rays is better with long waves than with short waves; or, to put it in another way, the loss of radiation by failure to turn the curve of the earth is greater with short waves than with long. The measurements made up to the present by Austin and his collaborators have extended to distances of only 900 miles, involving only very slight bending, and, besides, have not been very numerous.

still atmosphere be drawn round the globe they will be nearest the earth at places where the sun is on the meridian, and will rise away from the earth somewhat sharply at places where the sun is rising or setting. The regions in which the change from the day level to the night level takes place form a great circular band round the globe and inclined to the meridians at an angle depending on the season. This region of the atmosphere, since it is perpetually moving with the sun, will be in a highly disturbed electrical condition. Formation of ions is actively proceeding in one half of the great circle and recombination in the other, and these processes doubtless take place somewhat irregularly even in a still atmosphere—with the result that patches or banks of ionised air, analogous to the banks of fog met at sea—will transiently constitute this band in the middle atmosphere. The effect of such patches of variously ionised air on electric waves propagated through the region is, in view of the connection between the velocity of the waves and the concentration of the ions, certain to be difficult. The scattering by repeated refractions will tend to make the region impenetrable to waves directed through it. Hence it may be expected that the regularity of the propagation through the steadily ionised horizontal strata of the daytime will be greatly disturbed by the twilight transitional banks and patches, with the ultimate consequence that the sounds heard in the receiving apparatus will be greatly weakened.

The author's experience up to the present indicates that the existence or non-existence of clouds in the vicinity of the receiving station has but little influence on the intensity and character of the stray minima, or, for that matter (provided the day is not brilliantly clear), on signals received from any distance and any point of the compass. Whence we may conclude that the irregularly ionised band is situated above the ordinary cloud level. The twilight transitional region may therefore be regarded as a sort of curtain enringing the earth and occupying the middle atmosphere and not the lower. Thus it can affect only the trajectories of waves travelling from great distances. The weakening of such long-distance waves will probably be greater or less according as they have to penetrate the curtain more or less obliquely. In the case of the natural electric waves received by an antenna in England during the autumn and winter the origin of the waves must in general lie to the south. It is reasonable to suppose that tropical Africa will supply most of them. In that case, the twilight transitional band must have a very great and a relatively short-lived influence on the intensity of the strays heard in the telephones, for the path of the waves from the suggested source to the receiving station is nearly coincident with the twilight band. These suppositions accord precisely with the observed facts. The minimum

is sometimes a complete zero lasting for only two minutes or less. Assuming that in this case the source of the natural electric waves and the receiving station lie both on the great circle of twilight, we deduce that the twilight band is at least 30 miles wide, this being the distance the earth rotates eastward in two minutes. In addition, the same assumption would indicate that the principal source of the strays during November, 1909 and 1911, lay in the direction of the eastern portion of the Atlas Mountains.

Again, the observations have shown that the chief twilight minima occur about 10 minutes before sunrise and about 10 minutes after sunset during the same periods. This fact is accounted for by the consideration that the time of sunrise in the middle atmosphere is a little earlier and the time of sunset a little later than at the surface of the earth. In this connection it should be noticed that the electrically effective sunrise at a point in the middle atmosphere, as measured by the ionising power of the sunlight reaching the point, is not coincident in time with the sunrise at the same point as indicated by mere luminosity, that is, with the geometrical sunrise. The rays heralding the sunrise in the latter and ordinary sense must possess very little ionising power, for the reason that in passing the earth tangentially they have traversed so long a path in the lower atmosphere as to have lost their ionising radiation. Thus an observation of the time interval of the stray minimum before geometrical sunrise and after sunset does not determine the height of the electrically disturbed regions. Besides this, the exact time of the stray minimum will be affected to some extent by the obliquity of the ionic curtain to the line of propagation of the waves.

During the day the electric waves travel in the relatively narrow shell of dielectric between some stratum in the middle atmosphere and the surface of the earth. At night they travel in the much wider shell of dielectric between the assumed high conducting layer and the earth. In England, in winter, the day strays are much weaker than the night strays. From this we might conclude either that the aggregate absorption in the thin shell of dielectric is greater than in the deeper night shell, or that the ionisation of the middle atmosphere during the day is sufficiently non-uniform to hinder the propagation of the waves. But another factor must be recognised. The electric disturbance produced by a lightning discharge is doubtless impulsive in character, and is probably either a solitary wave or a very short train of waves. The study of the refraction of such disturbances leads to some well-known theoretical difficulties, but if we assume that the wave undergoes dispersion during its progress through the ionised middle atmosphere, then the disturbance arriving at a given receiving station should exhibit a fairly definite frequency, and that arriving at a station at a different distance should

exhibit a different frequency; or, in other words, there should be a distinct best frequency at which to adjust the receiving apparatus at each of these stations. This is on account of the difference of trajectory that difference of frequency brings. There is but little experimental evidence bearing on this point, though what there is favours the assumptions; but clearly if dispersion do occur in the sunlit middle atmosphere, and do not occur at night, the weakness of the day strays is fully accounted for without invoking the assistance of absorption.

Though the hypothesis of propagation round the earth by refraction in the ionised middle atmosphere has now been applied to the problem that prompted it, namely, the explanation of the minimum phenomenon of natural electric waves, yet it seems desirable to enquire how the hypothesis comports itself towards the known facts and properties of the artificial electric waves used in signalling.

The two assumptions on which the discussion has so far been built are, first, that there exists in the atmosphere a permanently conducting upper layer which is somewhat sharply defined, and which therefore reflects waves of every frequency—we may call it Heaviside's reflecting layer; and, second, that in the day (and only to a slight and erratic extent in the night) the atmosphere below this reflecting layer is ionised in nearly horizontal strata, the ionisation diminishing as the earth's surface is approached, with the result that electric waves are given a bent trajectory and the Heaviside layer put out of action. In using these assumptions in what follows, the atmosphere will be supposed at rest.

One of the most important of the facts known concerning the transmission of artificial waves is the difference between day and night signals discovered by Marconi* in 1902 during a voyage from England to New York. He found that there was little difference between day and night signals at distances less than 500 miles from the sending station, but that the day signals were unreadable at distances of 800 miles and more, while the night signals were readable up to distances of 2000 miles. This is possibly due to the same causes as the weakening of the day strays relatively to the night strays, but is most probably due to the failure of the heterogeneously ionised air to bend the waves sufficiently to fit the convexity of the earth. Thus, in explaining the daylight effect observed first by Marconi in 1902, it is only necessary to suppose that the relatively short waves then in use travelled to great heights in the atmosphere on account of the smallness of the curvature of their trajectory, and were not refracted sufficiently to

* Marconi, 'Roy. Soc. Proc.,' June, 1902.

reach the earth again in appreciable amount. This would probably not have happened with longer waves.

As for the night signals, both long and short waves are propagated through the lower and middle atmosphere in straight lines to great heights and reflected at the Heaviside layer, and then they descend to earth again, having suffered comparatively little absorption. The waves may be imagined to creep round this electrical vault of the atmosphere in a manner somewhat analogous to the creeping of sound round a whispering gallery, being plentifully scattered downward in their progress by the irregularities in the reflecting surface, or, to put it another way, we may imagine that a transmitting station "lights up the sky," in an electrical sense, for many degrees below its horizon.

Since in the observations quoted the daylight signals were perceptible at 700 miles, where the horizontal plane of the sender crosses the observer's vertical at a height of 60 miles, we may conclude that the trajectory of the radiation directed horizontally from the sender does not reach higher than 30 miles in the daytime. It may be mentioned at this point that Marconi originally suggested that the phenomenon might be due to a possible discharging action of sunlight on the sending antenna, and J. J. Thomson considered it rather due to the absorption of energy by the ionised air in the immediate neighbourhood of the antenna, but both these explanations ought to make the contrast between day and night signals the same for short distances as for long, which is not the case.

The above considerations suggest that there should exist a best frequency for signalling over great distances. Now the radiation from a Hertzian oscillator is most intense in its equatorial plane, and therefore, from a vertical linear earthed antenna, is most intense in the horizontal plane of the sending station. Hence we conclude that the best frequency is that for which, in a given ionic condition of the atmosphere, the trajectory of the radiation which starts nearly horizontally returns to the earth's surface near the receiving station. Marconi has stated* that a wave-length of 5000 metres is almost always better than one of 4000 metres for Transatlantic signalling—though, he remarks, the shorter wave-length is better than the longer occasionally. In this connection it may be pointed out that, if the transmission of signals be attempted with an exceedingly long wave-length, the aggregate curvature produced by the ionic refraction in the day might be sharper than the curvature of the earth. This would cause the nearly horizontal radiation to be turned down to the earth within a relatively short distance from the radiator. In that case reception at a distance would be

* Nobel Lecture, December, 1909.

carried on with radiation that had started at considerable upward inclination, and would therefore be accomplished with difficulty. The wave-fronts arriving at the receiving station would also be tilted forward considerably, and consequently the horizontal component of the electric field of the waves might approach the magnitude of the vertical component. In this case an inclined antenna would be a better receiver than a vertical one.

In various parts of the world it has been found that stations on the opposite sides of a mountain chain can communicate in the night with ease, though only with great difficulty, if at all, in the day. This is especially the case if a short wave is in use, and such a pair of stations can sometimes establish day communication by adopting a longer wave-length. It is, in fact, now common knowledge that for communication across hilly country in the daytime, a long wave—a thousand metres or more—should be used. The explanation is obvious on the hypotheses developed above. The rays, starting with sufficient elevation from a sending station in the plains, travel in straight lines through the lower atmosphere past the mountain tops, and then, reaching the middle atmosphere, are deflected downward by refraction in the ionised air. Short waves are refracted much less than long waves, and are therefore not bent so fully into the lower atmosphere as are the long waves. Indeed, the short waves may be entirely lost, and the long waves be bent down abundantly and come to earth again on the far side of the mountains. In the night, however, the ionisation of the middle atmosphere has disappeared, the Heaviside layer is open, and waves of all frequencies are reflected down to earth again. Another fact that emphasises the existence of elevated trajectories is afforded by the experiences of the Alpine receiving stations. These stations commonly receive signals from great distances in all directions—from stations in all parts of Europe and from ships on the Atlantic—so that it has been said that "the Alps attract signals." Stations in the plains do not get these distant signals nearly so often. The fact is that the high mountain stations have, of course, a much better chance of lying on the trajectories of the waves, or, as suggested by Larmor, in a slightly different connection, of "tapping a stronger stratum of radiation."

Recently, in an evening discourse at the Royal Institution, Marconi has described* the striking effects of sunrise and sunset on the strength of signals received from across the Atlantic Ocean. He stated that the intensity of the signals received at Clifden, Ireland, from Glace Bay, Canada, remains fairly steady during the day, but shortly after sunset at Clifden it becomes gradually weaker, and reaches a minimum in about

* June 2, 1911.

two hours. It then begins to strengthen, and finally reaches a maximum—sometimes a very high one—at the time of sunset at Glace Bay. During the night the signals are very variable in strength, varying from very weak to very strong. Shortly before sunrise at Clifden the signals grow stronger, and reach a high maximum shortly after sunrise; they now dwindle to a marked minimum about two hours after, and then they return gradually to their normal day strength. The ratio of the intensity of the signals during the twilight maximum to the average intensity throughout the day is much greater for a wave 5000 metres long (frequency 60,000 per second) than for a wave 7000 metres long (frequency 43,000 per second), and the long wave signals are uniformly stronger during the day than those of the shorter wave.

Some of these observed facts can be understood by the aid of the hypothesis of ionic refraction. We have only to lay down the principle that the aggregate curvature of the trajectory of the longer waves is nearer to the curvature of the earth than that of the shorter waves, or, in other words, that the daylight trajectory of the longer waves is more suited than that of the shorter waves to the distance between the Irish and Canadian stations. Again, the minimum that occurs at about two hours after sunset at Clifden is readily explained by the conception, already discussed, that in the twilight regions the recombination of ions has consequences equivalent to a somewhat opaque curtain hanging from the top to the bottom of the middle atmosphere. Moreover, at two hours after sunset at Clifden the sun is setting at a place between the stations about 650 miles from Glace Bay. At this place the horizontal plane of Glace Bay passes between 50 and 60 miles overhead. If now we assume that the height of the curtain of irregularly ionised air is of the order 50 miles, thus making no allowance whatever for the bending of the rays from Glace Bay in their progress below that level, we see that the signals transmitted to Clifden are weakest when the curtain comes on the horizon of the sending station. If, on the other hand, we allow for the likelihood of the rays following considerably bent paths even in the lower middle atmosphere, we must take Marconi's results as showing that the ionic curtain reaches effectively to much lower atmospheric levels than 50 miles. All of this applies, *mutatis mutandis,* to the morning minimum produced by the sunrise belt passing between the stations.

In regard to the remaining point quoted from Dr. Marconi, namely, the strong maximum in signals to Clifden at about sunset at Glace Bay, and before sunrise at Clifden, there is more difficulty in finding an explanation. It would seem that the heterogeneous ionisation following the twilight

through the atmosphere can give rise to somewhat regular reflections, so that when it passes over and behind the sending station it changes from being a hindrance to being a help in signalling. This view contains nothing that is fundamentally inadmissible. But the reflecting process was observed to be better with short waves than with long; perhaps the following considerations may in some degree account for this. First, it is known from general electromagnetic principles that when a wave crosses layers of changing refractive index there is a reflected wave propagated backwards, and this reflected wave is the more intense the greater the change in index. Second, let us assume that the surfaces of equal ionisation rise from the day level to the night level in a long slope extending over, perhaps, a hundred miles from east to west through the twilight belt, being rather broken of course, by irregularities in the changing ionisation. On account of the broken character of the belt reflection from the sloping surfaces will be irregular. But it will be more irregular for the more refrangible radiation, that is to say, will be more irregular for waves of low frequency than for waves of higher frequency. Perhaps with this may be conjoined the fact that the frictional absorption suffered by the longer wave is greater than that suffered by the shorter.

The phenomena just discussed are to some extent noticeable over relatively short distances. The following curves are drawn from observations of the intensity of signals from Clifden as heard at the author's laboratory in London, the measurements being made by balancing the intensity of the Clifden signals against the adjustable intensity of locally produced artificial signals of about the same acoustic frequency. On the curves the intensities are plotted in arbitrary units as ordinates, with the times of measurement as abscissæ. The observation had to be snatched, so to speak, at the moments when the station happened to despatch a message, and the points of observation are therefore often rather irregularly distributed. Fig. 7 shows two remarkable minima, which are produced, presumably, by the presence of the ionic curtain between the stations. Of these two minima,

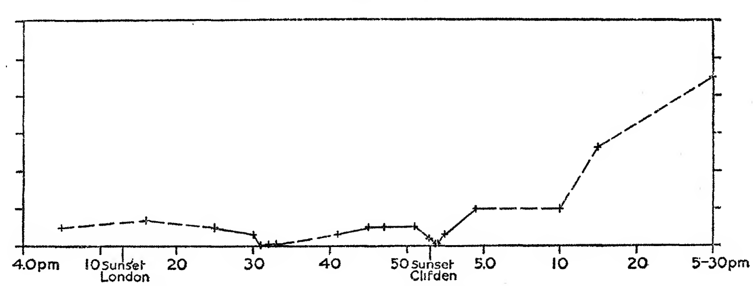

Fig. 7.—Intensity of Signals reaching London from Clifden, January 12, 1912.

the one that occurs most commonly—the phenomena vary greatly from day to day—is that one appearing when the sun is setting at a place about half-way between the stations. The minimum is fairly well marked in the sunrise curve shown in fig. 8. The reflections that are so pronounced a feature of Marconi's long-distance observations are not nearly so evident over short distances, according to the author's experience. But fig. 9 shows

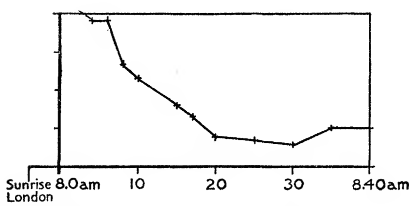

Fig. 8.—Intensity of Signals, January 25, 1912.

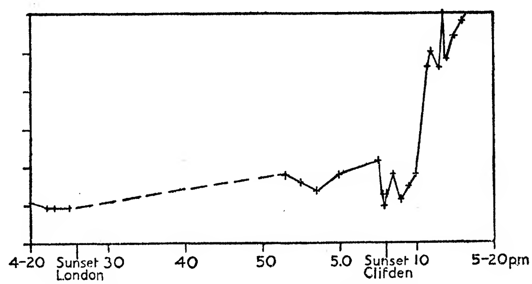

Fig. 9.—Intensity of Signals, January 20, 1912.

a case where the variations soon after sunset at Clifden were very decided. The curve does not do full justice to the phenomena, however. As a matter of fact the chief variations were so rapid and so wide that there was not time to measure them; indeed, on occasion, the changes in intensity are startling in their amplitude and swiftness.

It will be noticed that all the curves exhibit a great difference between the strength of the night signals and that of the day signals, although the distance is only 440 miles. Yet it is known that the same signals are heard at Glace Bay as strongly in the day as in the night. We gather from this that the daytime trajectory of the radiation passes well above places relatively near to the sending station and descends again, after overtaking the curvature of the earth, at the greater distance. It is well to recall here that in his recent experiments on the reception of signals from Clifden at distances up to 6000 miles, Marconi found the signals readable only at night at greater distances than 4000 miles—which seems to indicate that the trajectories of the rays in the daytime are such as to bring down within the distance named practically all the radiation starting, at all elevations, from the antenna.

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